

Analysis of Alfalfa Production in a Water-Stressed Region:

A Dynamical Modeling Approach

by

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## ABSTRACT

Alfalfa is a major feed crop widely cultivated in the United States. It is the fourth largest crop in acreage in the US after corn, soybean, and all types of wheat. As of 2003, about 48% of alfalfa was produced in the western US states where alfalfa ranks first, second, or third in crop acreage. Considering that the western US is historically water-scarce and alfalfa is a water-intensive crop, it creates a concern about exacerbating the current water crisis in the US west. Furthermore, the recent increased export of alfalfa from the western US states to China and the United Arab Emirates has fueled the debate over the virtual water content embedded in the crop. In this study, I analyzed changes of cropland systems under the three basic scenarios, using a stylized model with a combination of dynamical, hydrological, and economic elements. The three scenarios are 1) international demands for alfalfa continue to grow (or at least to stay high), 2) deficit irrigation is widely imposed in the dry region, and 3) long-term droughts persist or intensify reducing precipitation. The results of this study sheds light on how distribution of crop areas responds to climatic, economic, and institutional conditions. First, international markets, albeit small compared to domestic markets, provide economic opportunities to increase alfalfa acreage in the dry region. Second, potential water savings from mid-summer deficit irrigation can be used to expand alfalfa production in the dry region. Third, as water becomes scarce, farmers more quickly switch to crops that make more economic use of the limited water.

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## TABLE OF CONTENTS

	Page
LIST OF TABLES .....	iv
LIST OF FIGURES .....	v
CHAPTER	
1 INTRODUCTION .....	1
2 BACKGROUND .....	9
3 METHOD .....	15
3.1 Model Framework .....	15
3.2 Model Description.....	16
4 RESULTS .....	27
4.1 Baseline Model .....	28
4.2 Three Scenarios.....	30
4.3 Simulation Results .....	33
5 CONCLUSION AND DISCUSSION .....	36
REFERENCES.....	40
APPENDIX	
A LIST OF SYMBOLS AND DEFAULT PARAMETER VALUES .....	43
B MATLAB CODE .....	46

## LIST OF TABLES

Table	Page
1.1. Top 4 Largest Crops in Acreage and Value in the US in 2013 .....	3
2.1. Aridity Index Across Climatic Spectrum .....	12

## LIST OF FIGURES

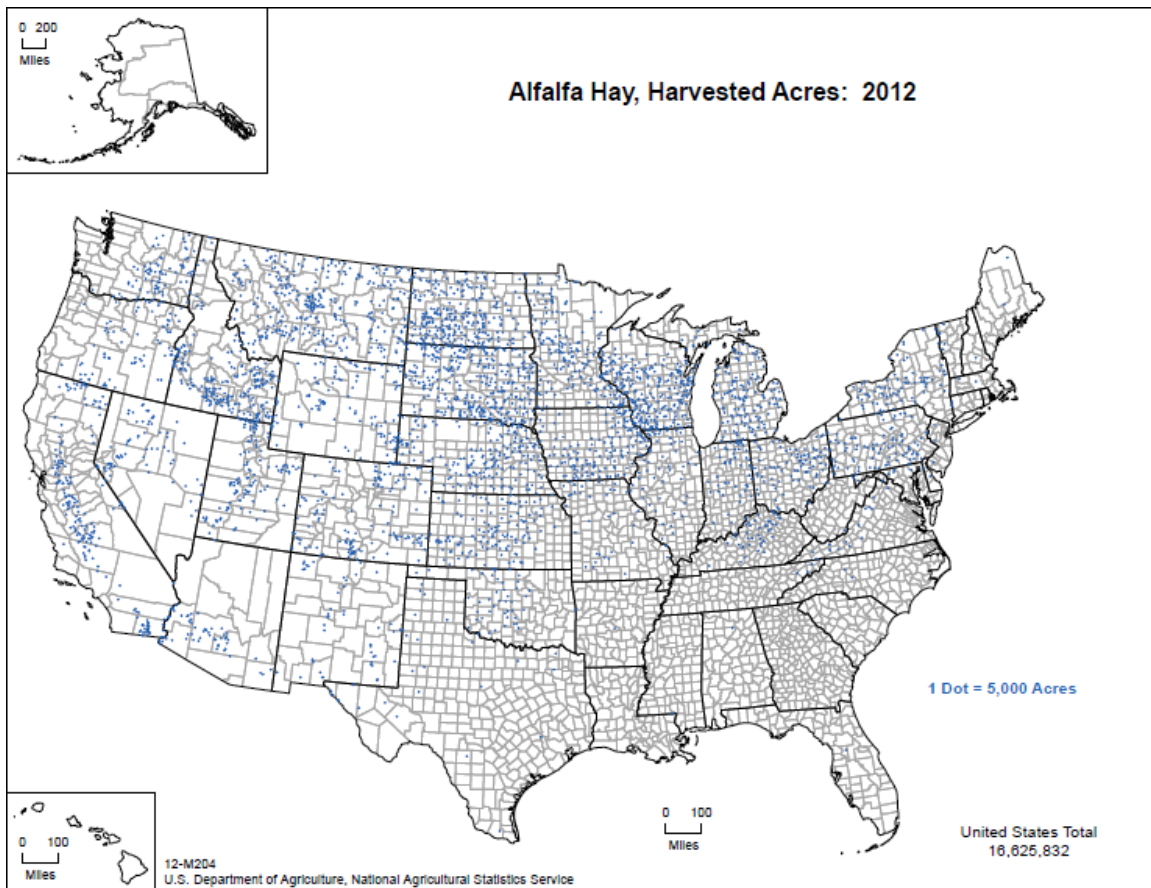
Figure	Page
1.1. Harvested Acres of Alfalfa Hay in 2012 .....	1
1.2. Acreage of Irrigated Harvested Cropland as Percent of All Harvested Cropland Acreage in 2012 .....	4
1.3. Harvested Acreages of Irrigated Alfalfa Hay in 2012 .....	4
1.4. Partitioning of Green and Blue Water Consumption of Alfalfa .....	4
1.5. Alfalfa Acreage Changes in the Western States and Non-Western States from 2003 to 2014 .....	7
1.6. Change in Alfalfa Hay Acreage Harvested from 2007 to 2012 .....	8
2.1. Acreage Change Devoted to Corn for Grain and Soybeans for Beans from 2007 to 2012 .....	11
2.2. Harvested Acres of Vegetables in 2012 .....	11
3.1. Cropland-use Change Framework .....	16
3.2. Partition of Precipitation into Stream Runoff and Evapotranspiration ...	23
3.3. Budyko Curves of Alfalfa ( $v_A=3$ ) and Other Crops ( $v_B=1.5$ ) .....	24
4.1. Time Series of Fractions of Crop Areas and Crop Prices and Phase Plane of Fractions of Crop Areas of the Baseline Case .....	28
4.2. Alfalfa Hay Exports from 2007 to 2013 .....	30
4.3. Yield Response to Evapotranspiration for Alfalfa, Corn, Soybeans, Sunflowers, and Winter Wheat .....	32
4.4. Phase Portraits of Different Levels of International Demands for Alfalfa	33
4.5. Phase Portraits of Different Levels of Midsummer Deficit Irrigation in the Dry Region .....	34
4.6. Phase Portraits of Different Levels of Precipitation in the Dry Region ....	35

## CHAPTER 1

### INTRODUCTION

Alfalfa (*Medicago sativa* L., also known as *lucerne*) is a perennial forage crop widely cultivated in the United States. In 2012, the US acreage devoted to alfalfa hay was 16.6 million acres, or 4.27% of the total cropland. Figure 1.1 shows that alfalfa is primarily grown in the West, Midwest, and East, but not commonly in the southern US.

As a regional source of feed crop, alfalfa has supported dairy, beef, and horse



**Figure 1.1.** Harvested acres of alfalfa hay in 2012. One blue dot corresponds to 5,000 acres. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)

industries in the US (Martin, Mertens, & Weimer, 2004). In particular, it has been an important feed for dairy farms due to its high levels of protein and low fiber (Glennon, 2009; Robinson, 2014). According to Robinson (2014), alfalfa hay has the combination of nutritional features beneficial for milk cows that most other feedstuffs do not possess. Furthermore, when fed low-quality alfalfa, a dairy cow produces at least less than 50% of its potential milk (Glennon, 2009). For this reason, alfalfa production is closely associated with the dairy industry. Alfalfa utilization by dairy cows is about 75 – 80 % of alfalfa usage in the leading dairy states such as California and Wisconsin (Summers et al., 2008). As alfalfa will likely remain an irreplaceable portion of the diets for high milk producing cows, the dairy industry is likely to drive alfalfa production in the future.

Apart from alfalfa's role for dairy cows, it has several traits that make it attractive to farmers. First, it is drought tolerant. Its deep root system allows it to draw on soil moisture reserves in water-limited settings while improving soil structure (Confalonieri & Bechini, 2004). Also, it has the ability to enter dormancy under continued dry conditions. Once it is relieved from moisture stress, alfalfa recovers its normal growth stage. These traits make it less susceptible than other crops to loss of yield caused by extended dry periods (Bauder, Hansen, Lindenmeyer, Bauder, & Brummer, 2011). Second, alfalfa is moderately salt tolerant. Soil salinity restricts crop growth and subsequently reduces crop yield (Tanji & Kielen, 2002). Because farmers need to use less water to leach salts from the soils when growing alfalfa, alfalfa is better adapted to dry conditions with high soil salinity than other salt sensitive crops. Third, alfalfa has high yields among other forage crops (Confalonieri & Bechini, 2004). In 2013, Arizona's alfalfa yield was 8.1 tons per acre, followed by California's 6.8 tons per acre, while the national average was 3.24 tons per acre. Fourth, alfalfa fixes nitrogen with its roots, which improves soil fertility. Putnam et al. (2001) conservatively estimated that about

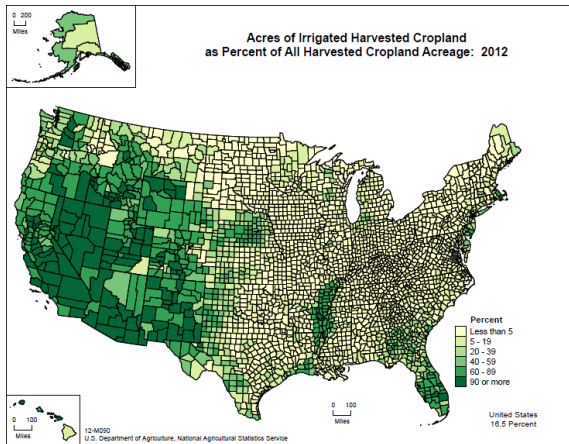


20% of alfalfa acreage is rotated to another crop each year in the US. In particular, it is typically rotated with corn, wheat, and barley, as well as high-value crops such as tomatoes and lettuce (Putnam et al., 2000). Moreover, because alfalfa can self-produce nitrogen for itself, it does not require extra nitrogen fertilizer for optimal growth (Putnam et al., 2001). Lastly, alfalfa is a key rotation crop capable of suppressing plant disease. In general, alfalfa's high level of adaptability and versatility is central to its wide cultivation.

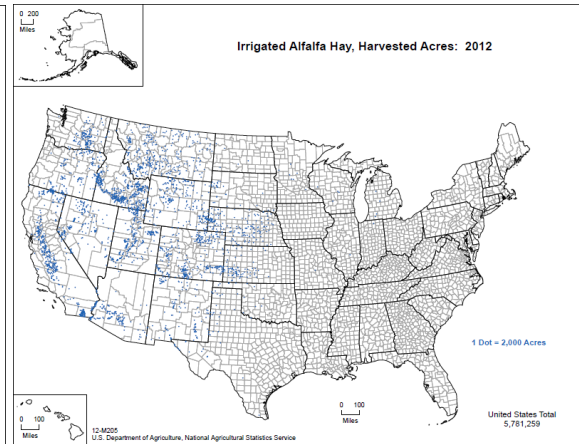
Today, alfalfa is the fourth largest crop in acreage in the US after corn, soybean, and all types of wheat (see Table 1.1). Moreover, alfalfa is worth \$11.8 billion as of 2013, again the fourth largest economic crop in the US after corn, soybeans, and all types of wheat. According to Putnam et al. (2000), alfalfa ranks first, second or third in crop acreage in almost all western states. As a nitrogen fixer that is both salt and drought resistant, alfalfa has become well adapted to the arid western regions of the US under irrigation. As of 2013, 27.7 million tons of alfalfa, or 48.2% of the total US alfalfa hay, was produced in the 11 western states from Colorado and westward, namely, Arizona, California, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming.

**Table 1.1.** Top 4 largest crops in acreage and value in the US in 2013. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)

Crop types	Area harvested (1,000 acres)	Value (1,000 dollars)
Corn for grain	87,668	97,476,029
Soybean for beans	75,869	49,332,495
All types of wheat	45,157	17,037,560
Alfalfa	17,763	11,852,087

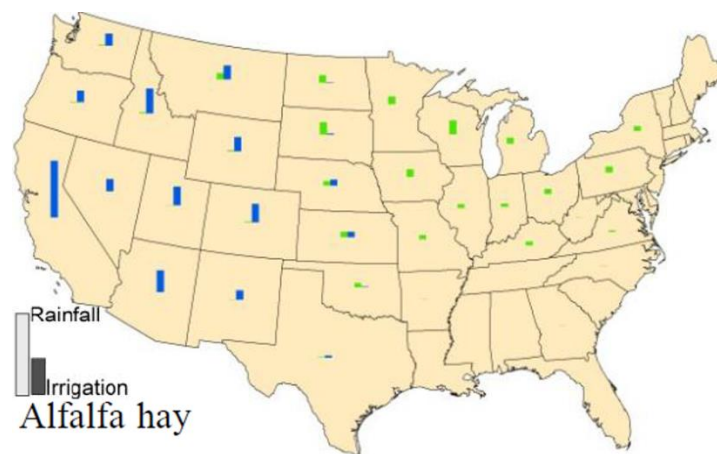


**Figure 1.2.** Acreage of irrigated harvested cropland as percent of all harvested cropland acreage in 2012. The relative magnitude is denoted by the progression of shades. As the percentage increases, the color deepens. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)



**Figure 1.3.** Harvested acreages of irrigated alfalfa hay in 2012. One blue dot corresponds to 2,000 acres. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)

In most arid western states, however, the farming is almost impossible without irrigation. Nationally, about 16.5% of the total harvested cropland was irrigated in 2012. Figure 1.2 indicates that the majority of the western region relies on irrigation, along with the west side of the Mississippi River and some parts of Florida. In the case of alfalfa, it was grown on 10.4% of irrigated land in the US in 2012, and most irrigated alfalfa hay production was concentrated in the 11 western states (see Figure 1.3).



**Figure 1.4.** Partitioning of green and blue water consumption of alfalfa. The green bar (left side) and the blue bar (right side) denote rainfall and irrigation, respectively ( $Mm^3$  per year). (Source: adapted from Mubako and Lant (2013))

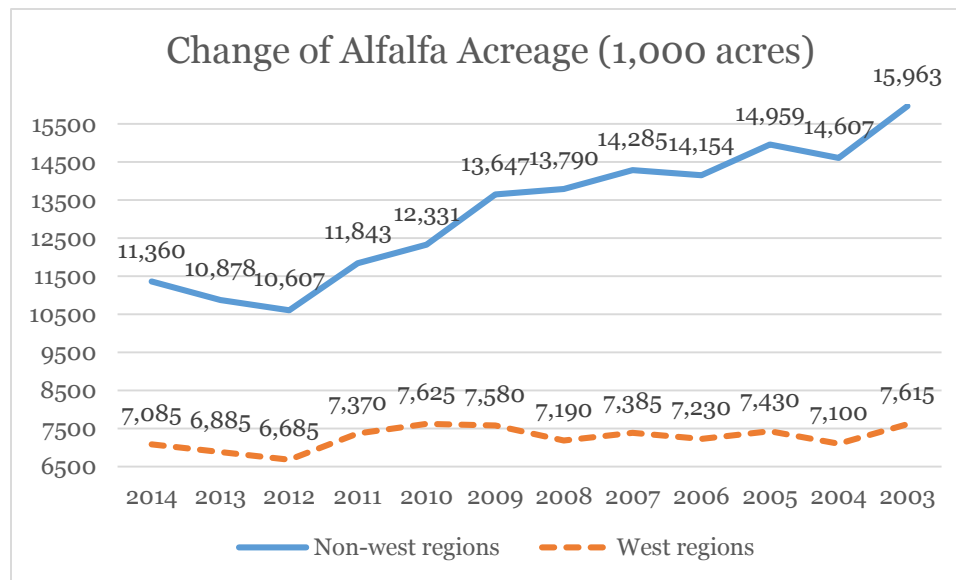
The work of Mubako and Lant (2013) also demonstrates that alfalfa grown in the 11 western states is heavily dependent on irrigation water, while the Midwest and East seem to have sufficient rainfall for the growth of alfalfa (see Figure 1.4). According to Summers et al. (2008), irrigated alfalfa accounts for more than 90% in the 11 western states, although there are some regions with dryland alfalfa like Montana. In order to sustain their farms, irrigation water has been a necessity for most alfalfa farmers in the US West.

The problem is that the West is experiencing more and more severe water stress. Irrigation water has two major sources: surface water and groundwater. In the West, a majority of water comes from snowpack in the mountains (Glennon, 2009). Snowpack reserves snow into the spring thaw, and then snowmelt provides water to rivers, lakes, and reservoirs that supply year round water. According to Siegler (2015), about a third of California's water is provided by snow. In 2014, more than 400,000 acres of California's cropland were fallowed due to limited water supplies (Siegler, 2015). Moreover, California issued a first-ever mandate reducing all non-agricultural water usage by 25% due to the record-low snowpack in the Sierra Nevada mountains. On the other hand, farmers can use groundwater to supplement limited surface water. However, as groundwater reserves decrease, the cost of pumping water from aquifers has been increasing, making groundwater withdrawals less viable. Some wells have even dried up. Extended dry periods, below-average snowpack, and rising energy cost of drilling and pumping groundwater from deeper sources will eventually place pressure on farmers to use water more efficiently.

Due to its large crop acreage and high dependence on irrigation, alfalfa has recently become a focus of the blame for high agricultural water consumption. Alfalfa requires more water than most crops because it has a deep root system, a dense canopy, and particularly, a long growing season (Bauder et al., 2011; Shewmaker, Allen, &

Neibling, 2013; Stanberry, 1955). Glennon, Libecap, & Culp (2014) point out that generally, it takes approximately 494  $m^3$  or 0.4 acre-foot of water to produce a ton of alfalfa, while roughly 5 tons of head lettuce can be produced using the same amount of water in Yuma, Arizona. Therefore, it is criticized that water is used to grow low-value, water-intensive crops like alfalfa in the arid US West since this is not considered the best way of utilizing scarce water in terms of generating economic value (i.e., more crop per drop). Moreover, Hoekstra (2014) points out that using scarce water to grow feed like alfalfa for milk and beef cows is not an efficient (or direct) way of producing food (i.e., more nutritional value per drop). Furthermore, the recent increase in alfalfa exports from the US West due to growing demand from international dairy industries and the trade imbalance with China has triggered a heated controversy over water embedded in alfalfa. The argument is that exporting the limited western irrigation water in the form of alfalfa counts against the national and regional water security and thus, is even immoral (i.e., drop for whose benefit) (Culp & Glennon, 2012; Glennon et al., 2014). In short, addressing the issue of water-use efficiency in terms of “how, why, and for whom alfalfa is grown” is a common thread running through all these criticisms of alfalfa production in the western US.

To confront water shortages, then, the general recommendation from critics is that the western states grow less alfalfa and switch it to higher-value, lower water-intensive crops to secure water resources. These concerns are supported by examining how the alfalfa production has changed over time in the West. Figure 1.5 illustrates the total acreage of alfalfa in the western and non-western regions for the years from 2003 to 2014. It shows a steady decline in alfalfa acreage in both regions, with non-western states

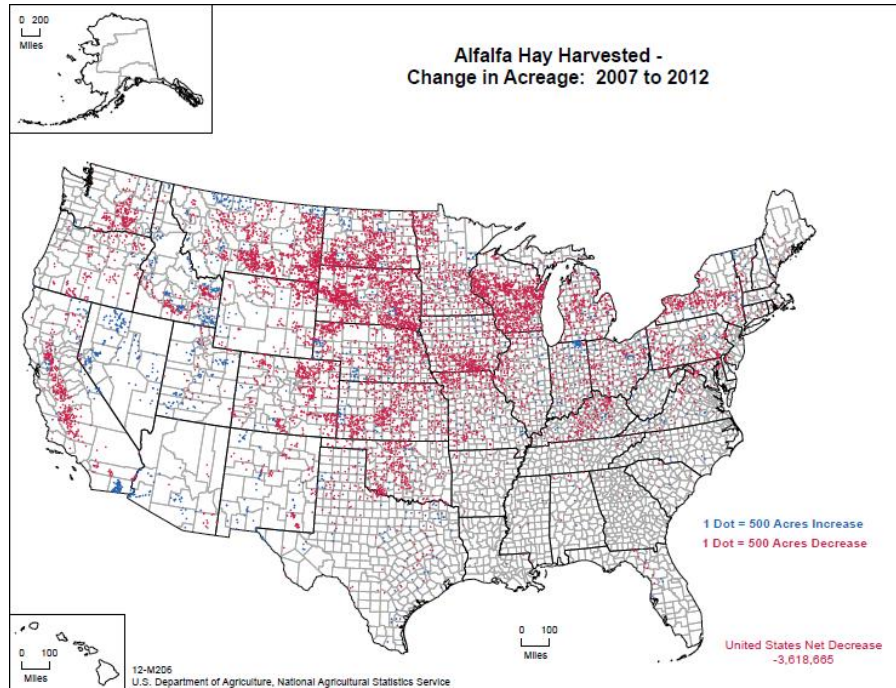


**Figure 1.5.** Alfalfa acreage changes in the western states (the dashed red line) and non-western states (the solid blue line) from 2003 to 2014. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)

showing a substantial reduction in alfalfa acreage of roughly 28.84%. The overall trend indicates that alfalfa acreage in the 11 western states has declined by about 6.96% from 7.6 million acres in 2003 to 7 million acres in 2014, although there have been some fluctuations in total alfalfa acreage throughout the time period. The difference between each region's rate of reduction in alfalfa acreage reflects a trend that alfalfa production is shifting out of rain-fed areas of the Midwest and East and into the arid West. Martin et al. (2004) remarks that as the number of dairy farms declines in the major dairy states in the Midwest, alfalfa hay production is shifting west with the rapid expansion of the local dairy industry. The 2012 Agricultural Census also supports this trend. Figure 1.6 indicates that most acreages reductions, denoted by red dots that correspond to 500 acres decrease in alfalfa acreage, occurred in the Midwest. Thus, the decrease of 3,618,665 acres from 2007 to 2012 is mostly attributed to acreage decline in non-western states.

Alfalfa production in the arid West is entangled with water scarcity in the region, weather conditions, and the market situation in and out of the country. Through the lens of alfalfa production in a water-stressed region, I aim to find policy implications for how farmers would respond to and cope with market changes and long-term climate change. A dynamical modeling offers a tool for understanding and identifying the important limiting factors of alfalfa production in the long term. Using a stylized model with a combination of dynamical, hydrological, and economic elements, I seek to answer the following research questions:

- What is the impact of international demands of alfalfa on crop production?
- What if farmers use less water to grow alfalfa at the expense of yield?
- How do long-term droughts relate to alfalfa production?



**Figure 1.6.** Change in alfalfa hay acreage harvested from 2007 to 2012. One blue dot corresponds to 500 acres increase; one red dot corresponds to 500 acres decrease. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services, Census of Agriculture for 2007 and 2012)

## CHAPTER 2

### BACKGROUND

In this chapter, I contextualize the assumptions underlying the analysis.

#### **Factors affecting alfalfa production**

Alfalfa production is influenced by alfalfa price expectations, the profitability of alternative crops, milk prices, the prices for corn and soybeans, and water availability and costs (Butler, 2010). These factors are all incorporated into the model, except for the expected prices of crops. In this study, farmers make production decision by maximizing the profit from the use of a given cropland area. Profitable milk prices induce an increase in the demand and price for alfalfa. Corn and soybeans are considered as the alternative crops. Water availability and costs are major limiting factors of alfalfa production.

Only market valuation of alfalfa (i.e., value in exchange) is taken into consideration for the purpose of this study. Alfalfa hay fed on farms (i.e., value in use) is not considered in the model, which means that all produced alfalfa is marketed off the farm. Because most alfalfa grown in the Midwest and East is fed on farms, this explains a huge underestimation of alfalfa acreage in these regions in my analysis results. In addition, the non-market values, such as rotation value for subsequent crops, scenic value, and other environmental values, are excluded in the analysis. Thus, the model results will be underestimated compared to actual data.

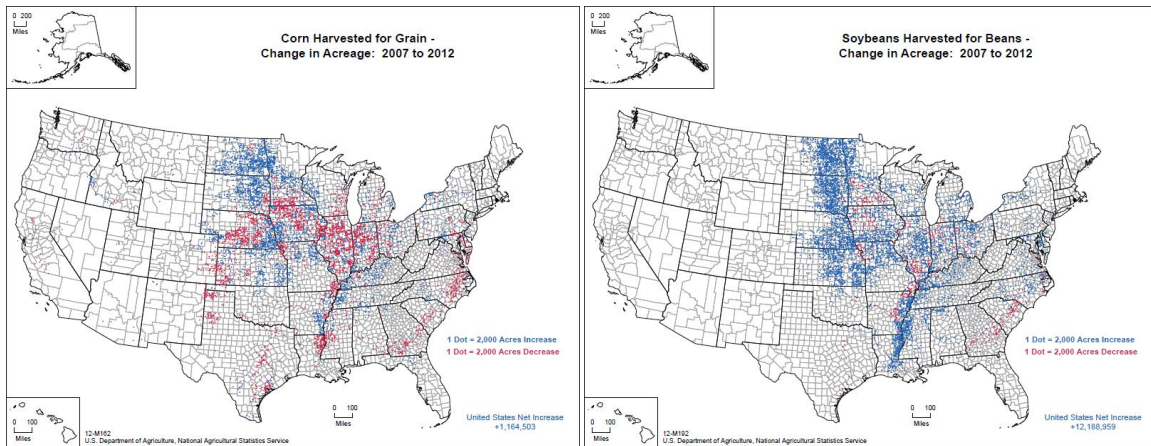
## **High/low-value crops**

Alfalfa is, in general, classified as a low-value crop. That is, it is presumed that alfalfa generates lower income per unit of land area than other crops such as specialty crops (e.g., almond, lettuce, or broccoli). Provided that economics is the driving force of cropping decisions, one would expect the initial response to be the dominance of high-value crops over agricultural land. However, in reality, both low- and high-value crops are grown on farms in tandem with each other. It reflects heterogeneity of various conditions like climate and market risk, which enables alfalfa to “compete economically for water and land resources directly and equally with all crops” even without subsidy (Putnam, 2010). In economics, this coexistence of low- and high-value crops occurs where marginal profit of producing low-value crops equals marginal profit of producing high-value crops. In the analysis, high/low-value criterion is based on the comparison of crop prices in relative terms, rather than using the conventional presumption of alfalfa as a low-value crop in an absolute sense.

## **Alternative crops**

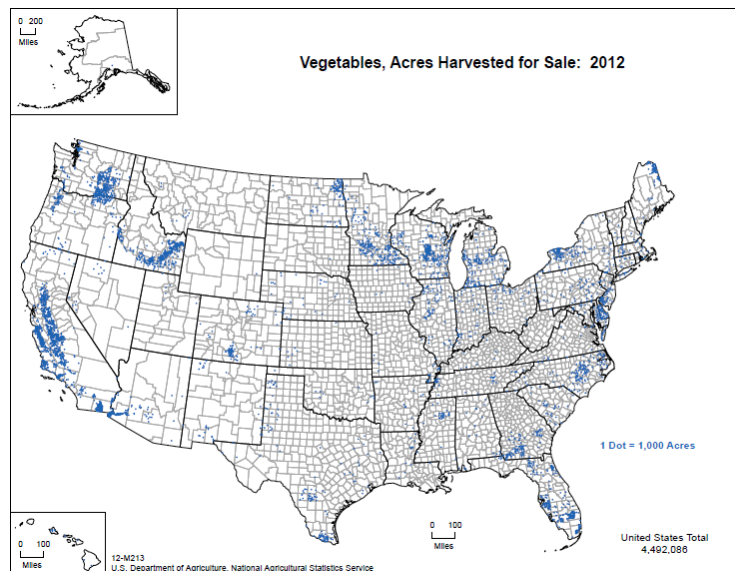
The change in alfalfa acreage depends on the existence of *profitable* alternative crops. Because virtually any crops cannot compete economically with urbanization and industries for limited land and water resources, I exclude non-agricultural sectors from the land-use change analysis. Only the agricultural sector competes for limited resources in the model.





**Figure 2.1.** Acreage change devoted to corn for grain (left) and soybeans for beans (right) from 2007 to 2012. One blue dot corresponds to 2,000 acres increase; one red dot corresponds to 2,000 acres decrease. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services, Census of Agriculture for 2007 and 2012)

Linking the recent decrease in alfalfa acreage from 2007 to 2012 in the Midwest and East to the increase in acreage devoted to corn and soybeans during the same time period (see Figure 2.1), corn and soybeans are selected to represent alternative crops that are less water-intensive than alfalfa. Vegetables are not representative of alternative crops due to their high regional concentration (see Figure 2.2).



**Figure 2.2.** Harvested acres of vegetables in 2012. One blue dot corresponds to 1,000 acres. (Source: U.S. Department of Agriculture, National Agricultural Statistics Services)

## Climate (the aridity index)

I define climatic zones using aridity. According to Maliva & Missimer (2012), aridity is an “essentially climatic phenomenon that is based on average climatic conditions over a region.” The aridity index is widely used to quantify how dry or wet a given location’s climate is. As the ration of potential evapotranspiration to precipitation, the aridity index indicates the number of times the precipitation received at a given location would evaporate. For example, the aridity index of five means that the energy at a given place can evaporate five times as much as precipitation received at the given place. For higher (or lower) values of the aridity index, a place gets drier (or wetter). The aridity index of 0.75 falls within the boundary between subhumid and humid climates, whereas the aridity index of 5 falls within the boundary between semiarid and arid climates (see Table 2.1). The aridity index will be discussed in more detail in the next chapter under crop water use section.

**Table 2.1.** Aridity index across climatic spectrum. (Source: Ponce, Pandey, & Ercan (2000))

Climatic types	Aridity index (AI)
Arid	$5 < AI < 12$
Semiarid	$2 < AI < 5$
Subhumid	$0.75 < AI < 2$
Humid	$0.375 < AI < 0.75$

## Salinity

High evapotranspiration rates cause the concentration of salts in the irrigation water. For this reason, in arid and semiarid regions, the surface water and groundwater

generally contain more salts than in humid and subhumid regions. Also, saline soils are naturally found in arid and semiarid regions. Soil salinity is a limiting factor of crop yield because soluble salts at the root zone are harmful to plant growth (Shahid, Taha, & Abdelfattah, 2013). Plants maintain their normal yield up to a certain threshold level of root zone salinity, but after exceeding it, crop yield declines linearly with the increase in the level of soil salinity. The degree of soil salinity is measured by using the electrical conductivity of soil saturation extract (in units of deci-siemens per meter,  $dS/m$ ). Salinity issues will be explored in more detail in the next chapter under yield section.

The salt resistant characteristic of alfalfa is factored in the model as one of the advantages of growing alfalfa in the arid regions. According to Tanji & Kielen (2002), however, both alfalfa and corn are designated as moderately sensitive crops with salinity threshold values of 2  $dS/m$  and 1.7  $dS/m$ , respectively. Even though alfalfa is slightly more salt tolerant than alternative crops of this study, the effect of soil salinity on crop yield would not make a major difference in crop distribution.

## **Water costs**

As discussed in the previous chapter, irrigation is generally necessary for alfalfa production in arid western states, while irrigation is not widely used in humid midwestern and eastern agricultural regions (see Figures 1.2, 1.3, and 1.4). Glennon (2009) mentions that farmers in the West usually pay a few pennies for a thousand gallons of water due to federally subsidized water and low-cost energy. In order to reflect the underpriced water in the model, the cost of irrigation water is designed to be around \$15 per acre-foot, or \$0.0006 per gallon of water in the West, while the water cost is set to be close to zero in the rain-fed areas.

In this framework, because water is used on a farm, private goods aspect of water is focused on the surface. First, more water consumption by one crop reduces the amount of water available for other crops. This rivalry over water is coupled with competition for land. In particular, it has a special significance in dry regions having scarce water. Second, it is possible to effectively exclude farmers who do not pay for water from water use. That is, farmers should pay for water whenever they use it, otherwise, they cannot use it. However, by setting market water rates to a relatively low level, public goods aspect of water is implicitly incorporated into the model. For the wet region where precipitation is sufficient for plant growth, water is actually treated as public goods coming down from the sky. In short, although water used on a farm is fundamentally private goods, it, in effect, counts as public goods through policy interventions for agriculture. This feature of water is reflected in the model by assuming that 1) crops are always fully irrigated (i.e., non-rivalry) and 2) farmers pay market water prices that are close to zero (i.e., non-excludability).

## CHAPTER 3

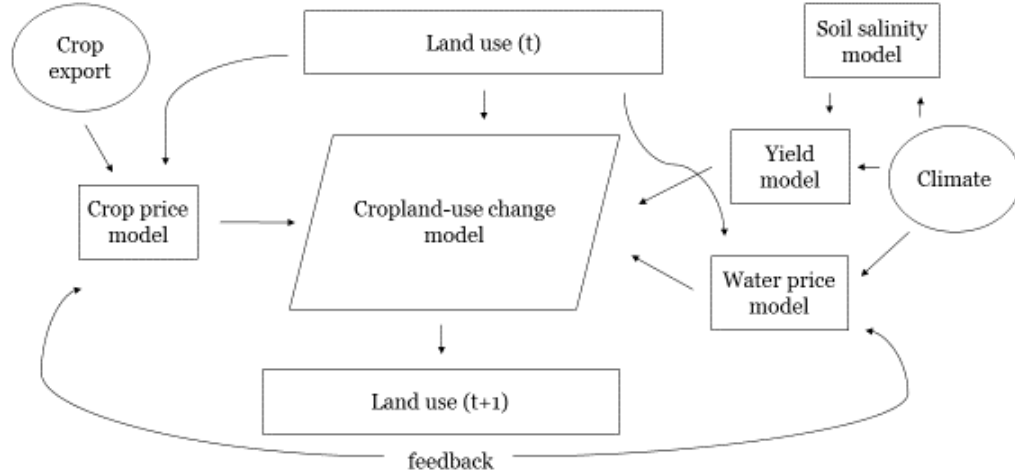
### METHOD

In this chapter, I introduce the land-use change model to analyze the causes and effects of alfalfa production dynamics. The model represents a cropland system of two climatic zones having different levels of aridity, i.e. dry and wet. Farmers are the only agents of decision-making in the model. They make crop-switching decisions by seeking the maximization of their net profits from cultivation (i.e., the most efficient use of the given cropland). They have the option of growing either alfalfa or other crops but do not leave the cropland fallow. Depending on their decision-making, spatial dynamics of the distribution of the two types of crops will change over time. The temporal trajectories of this crop distribution change are the main object of analysis in this study.

#### 3.1 Model Framework

In this section, I address the interactions and feedbacks between the cropland-use system and the economic and ecological subsystems. The decision of crop-switching is based on benefit-cost comparisons between alfalfa and other crops. The price and yield of crops determine the benefit; water and labor are the major components of the cost of growing crops. By changing the demand of irrigation water and the supply of crops, the cropland-use system creates feedback loops with the price models of water and crops. Crop exports and climate (i.e., aridity) are the critical exogenous forces of cropland-use

change. They influence farmers' decisions through the crop price model and the water price and crop yield models, respectively. The climatic factor also affects yield indirectly through the salinity model. The complexity of the modeling is illustrated in Figure 3.1, which is adopted and adjusted from Verburg, Schot, Dijst, & Veldkamp (2004).



**Figure 3.1.** Cropland-use change framework.

### 3.2 Model Description

Consider two regions: dry and wet. These two regions have limited arable land for agriculture,  $F_{dry}$  and  $F_{wet}$ , respectively. The size of the agricultural fields in the dry and wet regions is assumed to be equal,  $F_{dry} = F_{wet}$ . Farmers in these regions grow alfalfa (A) and other crops (B) like corn or soybeans to earn income. The rate of change of the fraction of the land devoted to alfalfa,  $\frac{dL}{dt}$ , is a function of the difference between net

revenues that farmers receive from growing A and B, on a per acre basis. The equation is given below.

$$\frac{dL}{dt} = rL(1 - L)[(P_A Y_A - C_A) - (P_B Y_B - C_B)]$$

where  $L$  is a fraction of the land devoted to alfalfa;

$t$  and  $r$  denote a time variable and a time-adjusting parameter, respectively;

$L(1 - L)$  represents a stabilizing factor that constraints a range of change;

$P_A$  and  $P_B$  are prices per ton of alfalfa and other crops (dollars/ton), respectively;

$Y_A$  and  $Y_B$  are average annual yields per acre of alfalfa and other crops (tons/acre), respectively;

$C_A$  and  $C_B$  are costs per acre of growing two crops respectively, measured in dollars (dollars/acre).

A positive value of  $\frac{dL}{dt}$  represents the amount of land originally devoted to other crops, but converted to growing alfalfa in the next year; a negative value means the opposite.

### **Price function ( $P$ )**

Price of an agricultural commodity is assumed to be determined by the quantities demanded and supplied of the market. As the quantity demanded increases, price increases (i.e.,  $\uparrow D \rightarrow \uparrow P$ ); as the quantity supplied increases, price decreases (i.e.,  $\uparrow S \rightarrow \downarrow P$ ).

$$P = \mu D^{b_1} S^{b_2}$$

$\mu$  is the price coefficient for a specific agricultural crop;

$D$  is the quantity demanded of the crop;

$S$  is the quantity supplied of the crop;

$b_1$  is demand elasticity of a crop price, the degree of responsiveness of the crop price to a change in the quantity demanded of the crop ( $b_1 > 0$ );

and  $b_2$  is supply elasticity of a crop price, the degree of responsiveness of the crop price to a change in the quantity supplied of the crop ( $b_2 < 0$ ).

In this model, for simplicity's sake, it is assumed that the demand elasticity of price is identical to the supply elasticity of price, regardless of the type of a crop (i.e.,  $b_1 = -b_2 = b$ ).

$$P = \mu \left( \frac{D}{S} \right)^b$$

So the price becomes a function of the relative quantity (or quantity ratio) of demand and supply.

Quantity supplied ( $S$ ) of a crop is the total amount of the crop that farmers produce and sell in the market. Because there are no agricultural imports from foreign countries, it is obtained by summing the quantities supplied by all farmers in both the dry and wet regions. The quantity supplied of each crop is:

$$S_A = F_{dry} L_{dry} Y_{A,dry} + F_{wet} L_{wet} Y_{A,wet}$$

$$S_B = F_{dry} (1 - L_{dry}) Y_{B,dry} + F_{wet} (1 - L_{wet}) Y_{B,wet}$$

where the type of crop is denoted by subscripts  $A$  and  $B$ , while the type of region is denoted by subscripts  $dry$  and  $wet$



Analogous to quantity supplied, quantity demanded ( $D$ ) of a crop is the total amount of the crop that consumers, directly and *indirectly*, purchase in the regional and *international* markets:

$$D = D^{(R)} + D^{(I)}$$

where  $D^{(R)}$  and  $D^{(I)}$  are the regional and international quantities demanded of the crops, respectively. Please note that international demands are factored into the model by assuming net exports of the crops.

Because milk production depends on the quantity and quality of feed (i.e., alfalfa hay) that dairy cows consume, the regional quantity of alfalfa demanded ( $D_A^{(R)}$ ) is derived from the demand for dairy products. This is supported by Glennon (2009) who mentions that alfalfa is *directly* used to produce milk in the dairy industry. Here, it is implicitly assumed that 1) the dairy industry is the only consumer of alfalfa, and 2) dairy cows are fed on alfalfa hay alone. In short, the demand for alfalfa is estimated by dividing the demand for milk by alfalfa productivity of producing milk. Alfalfa productivity of producing milk equals milk cows' efficiency of converting alfalfa into milk.

In order to estimate regional demands for each crop, it is assumed that there are only two agricultural goods that people can choose to buy for their food consumption: other crops (B) and dairy products (C) (certainly, not alfalfa). People acquire utility from consuming a particular set of those two goods. Through utility maximization under a budget constraint, I derive Marshallian *regional* demand functions of the two goods. People's preferences are represented in utility functions. Assuming that dairy products and other crops are independent goods, I use the Cobb-Douglas utility function. This indicates that quantity demanded of each good depends only on the price of that good, and not on the price of the other good.

$$\text{Maximize } U(x_C, x_B) = x_C^\alpha x_B^{1-\alpha}$$

$$\text{Subject to } P_C x_C + P_B x_B = M$$

where  $U(x_C, x_B)$  is a Cobb-Douglas utility function.  $x_C$  and  $x_B$  denote the quantities demanded (i.e., consumptions) of each good, C and B, respectively.  $P_C$  is the price of dairy products.  $\alpha$  is an income partitioning parameter for the good C, which lies inside the 0-1 range. So  $\alpha$  and  $(1 - \alpha)$  indicate the fractions of income spent on each good, C and B, respectively.  $M$  is income.

I solve the optimization problem using the Lagrange method.

$$G(x_C, x_B, \lambda) = x_C^\alpha x_B^{1-\alpha} + \lambda(M - P_C x_C - P_B x_B)$$

Take first derivatives and solve for first order conditions in  $x_C$ ,  $x_B$ , and  $\lambda$ .

$$\frac{\partial G}{\partial x_C} = \alpha x_C^{\alpha-1} x_B^{1-\alpha} - P_C \lambda = 0 \quad \Rightarrow \quad \alpha x_C^{\alpha-1} x_B^{1-\alpha} = P_C \lambda$$

$$\frac{\partial G}{\partial x_B} = (1 - \alpha) x_C^\alpha x_B^{-\alpha} - P_B \lambda = 0 \quad \Rightarrow \quad (1 - \alpha) x_C^\alpha x_B^{-\alpha} = P_B \lambda$$

$$\frac{\partial G}{\partial \lambda} = M - P_C x_C - P_B x_B = 0 \quad \Rightarrow \quad P_C x_C + P_B x_B = M$$

The regional quantities demanded for the goods C and B are:

$$D_C^{(R)} = x_C^* = \frac{\alpha M}{P_C}$$

$$D_B^{(R)} = x_B^* = \frac{(1 - \alpha) M}{P_B}$$

Please note that quantity demanded of each crop is proportional to income.

Thus, the regional quantity demanded of A is:

$$D_A^{(R)} = c D_C^{(R)} = c \frac{\alpha M}{P_C}$$

where  $c$  is a conversion rate of quantity demanded of dairy products to that of alfalfa (i.e., the inverse of alfalfa productivity of producing milk).

The total quantities demanded of alfalfa and other crops are:

$$D_A(P_C, D_A^{(I)}) = D_A^{(R)} + D_A^{(I)} = c \frac{\alpha M}{P_C} + D_A^{(I)}$$

$$D_B(P_B, D_B^{(I)}) = D_B^{(R)} + D_B^{(I)} = \frac{(1 - \alpha)M}{P_B} + D_B^{(I)}$$

So the prices of alfalfa and other crops are:

$$P_A = \mu_A \left( \frac{D_A}{S_A} \right)^b = \mu_A \left( \frac{D_A^{(R)} + D_A^{(I)}}{S_A} \right)^b = \mu_A \left[ \frac{c \frac{\alpha M}{P_C} + D_A^{(I)}}{F_{dry} L_{dry} Y_{A,dry} + F_{wet} L_{wet} Y_{A,wet}} \right]^b$$

$$P_B = \mu_B \left( \frac{D_B}{S_B} \right)^b = \mu_B \left( \frac{D_B^{(R)} + D_B^{(I)}}{S_B} \right)^b = \mu_B \left[ \frac{\frac{(1 - \alpha)M}{P_B} + D_B^{(I)}}{F_{dry}(1 - L_{dry})Y_{B,dry} + F_{wet}(1 - L_{wet})Y_{B,wet}} \right]^b$$

## Yield function ( $Y$ )

First, a yield function without effects of salinity ( $Y_m$ ) is specified by the following quadratic form:

$$Y_m = \beta \left( 1 - \left( \frac{W}{W^*} - 1 \right)^2 \right)$$

where  $\beta$  is the optimal average annual yield per acre under full irrigation  $W^*$ , and  $W$  is the amount of water applied to the crop. It is assumed that crops are always fully irrigated such that  $W = W^*$ .

To capture the effects of soil salinity on actual yield  $Y$ , a salinity-yield model that is developed by Maas & Hoffman (1977) is used.

$$\frac{Y}{Y_m} = 1 - \frac{d}{100} (EC_e - EC_{e,threshold}) \text{ when } EC_e > EC_{e,threshold}$$

where  $EC_e$  is mean electrical conductivity of the saturation extract for the root zone ( $dS/m$ );  $EC_{e,threshold}$  is electrical conductivity of the saturation extract at the threshold of  $EC_e$  when crop yield first reduces below  $Y_m$  ( $dS/m$ );  $Y$  is actual crop yield (tons/acre);  $Y_m$  is expected crop yield when  $EC_e < EC_{e,threshold}$  (tons/acre); and  $d$  is reduction in yield per increase in  $EC_e$  ( $\%m/dS$ ).

Thus, the crop yield when  $EC_e > EC_{e,threshold}$  is:

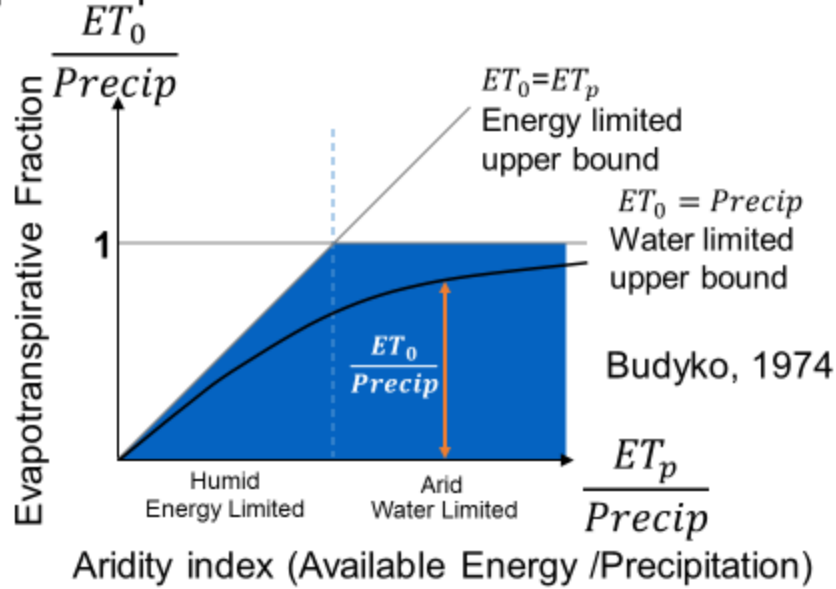
$$Y = Y_m \frac{Y}{Y_m} = \beta \left( 1 - \left( \frac{W}{W^*} - 1 \right)^2 \right) \left[ 1 - \frac{d}{100} (EC_e - EC_{e,threshold}) \right]$$

### **Crop water use ( $W^*$ )**

Crop water use refers to the amount of water consumed by a crop to grow optimally. More than 95% of the water consumed by plants is evaporated through plant leaves (i.e., transpiration) and soil or plant surfaces (i.e., evaporation). For irrigated crops that reaches full cover, the majority of water evaporation is from transpiration. Because the water lost from transpiration is directly linked to plant growth, evapotranspiration is used interchangeably with crop water use.

In order to estimate actual crop evapotranspiration for alfalfa and other crops, the reference crop evapotranspiration (i.e.,  $ET_0$ ) and the Budyko framework (1974) are used. The Budyko framework is a water balance partition framework that decomposes precipitation into runoff and evapotranspiration. When water, in the form of

## Partition of precipitation into stream runoff and evapotranspiration



**Figure 3.2.** Partition of precipitation into stream runoff and evapotranspiration. The evaporative fraction is the ratio of actual evapotranspiration (i.e.,  $ET_0$ ) to precipitation, while the aridity index is the ratio of potential evaporation (i.e.,  $ET_p$ ) to precipitation.

precipitation, is applied to crops in the field, a certain portion runs off the ground and the rest of it evaporates. This relationship is plotted in Figure 3.2. The evapotranspirative fraction of precipitation becomes actual precipitation for plant growth.

Crop water use or evapotranspiration is influenced by crop types among many other factors.  $ET_A$  and  $ET_B$  represent the water use of alfalfa and other crops, respectively. They are usually calculated by multiplying the reference crop evapotranspiration by crop coefficients,  $K$  (Allen, Pereira, Raes, & Smith, 1998).

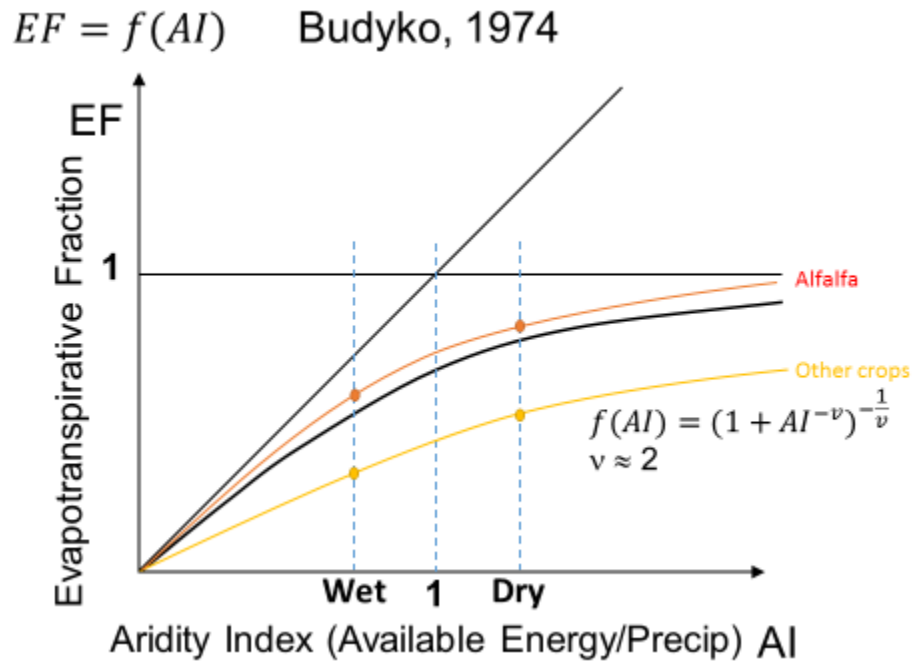
Figure 3.2 plots evapotranspirative fraction (i.e.,  $\frac{ET_0}{Precip}$ ) as a function of aridity index (i.e.,  $\frac{ET_p}{Precip}$ ). Because climate influences the growing season and growth stages of plants, it is important to note that the aridity index, as a dryness indicator, is directly linked to crop water use. For example, a certain crop grows slower in a hot climate than

in a warm climate (e.g. alfalfa), while the other crops grow faster in a warm climate than in a cool climate (e.g. corn). Through Budyko curve (1974), different evaporation ratios are obtained for different climate conditions (i.e., the aridity index). Figure 3.2 illustrates that evaporation ratio is higher in the dry region than in the wet region. As a functional form of Budyko curve, the Turc-Pike equation (Turc, 1954; Pike, 1964) is used to describe evaporation ratio as a function of aridity index.

$$EF_0 = [1 + AI^{-v}]^{-\frac{1}{v}}$$

where  $EF_0$  refers to evaporative fraction (i.e.,  $\frac{ET_0}{Precip}$ ),  $AI$  denotes the aridity index (i.e.,  $\frac{ET_p}{Precip}$ ), and  $v$  represents soil water storage (or retention) parameter ( $v > 0$ ).

In this study, the water requirements of alfalfa and other crops are estimated by multiplying the crop coefficients,  $K_A$  and  $K_B$ , to the soil storage parameter  $v$ . That is,  $v_A = K_A v$ , and  $v_B = K_B v$ . Because alfalfa has a deep root system that makes it less susceptible



**Figure 3.3.** Budyko curves of alfalfa ( $v_A=3$ ) and other crops ( $v_B=1.5$ ). The evaporation ratio is higher for alfalfa than for other crops under a given climate condition.

to water stress during dry periods,  $K_A$  is assumed to be greater than  $K_B$ , and therefore  $v_A > v_B$ . Graphically, the crop coefficients shift the Budyko curve close to or away from the water and energy limited upper bounds, making it a plant-specific Budyko curve (see Figure 3.3).

Crop water uses per acre for A and B,  $W_A^*$  and  $W_B^*$ , are calculated by multiplying the optimal yield by their virtual water content. Virtual water content represents the volume of water used to produce a unit of crop yield.

$$W_A^* = Y_A VWC_A$$

$$W_B^* = Y_B VWC_B$$

where  $VWC_A$  and  $VWC_B$  are virtual water contents of alfalfa and other crops, respectively ( $m^3/\text{ton}$ );  $Y_A$  and  $Y_B$  are yields of alfalfa and other crops, respectively (tons/acre).

Precipitation and irrigation water are the two main sources of crop water use. Particularly, in the dry region, irrigation is necessary to supplement insufficient rainfall. The irrigation water requirement,  $Irri$ , can be derived by subtracting actual precipitation,  $Precip \times EF$ , from crop water requirement,  $W^*$ .

$$W^* = Precip \times EF + Irri$$

$$Irri = W^* - Precip \times EF$$

where  $Precip$  and  $Irri$  denote the amounts of precipitation and irrigation water per acre ( $m^3/\text{acre}$ ).

So the irrigation water requirements are:

$$Irri_A = W_A^* - Precip \times EF_A$$

$$Irri_B = W_B^* - Precip \times EF_B$$

## Cost function (C)

The cost function primarily consists of irrigation water costs and labor costs, and a cost of land is implicitly embodied in the model setup even though land is not a limiting factor in the model.

$$C = P_W \times Irri + P_U \times U + E = P_W \times (W^* - Precip \times EF) + P_U \times U + E$$

where  $P_W$  is the price of water (dollars/ $m^3$ );  $P_U$  is hourly wage rate (dollars/hour);  $U$  is average labor hours per acre needed to grow crops (hours/acre); and  $E$  is a crop-specific extra lump sum cost (dollars/acre).

Analogous to crop prices, the water price is specified as a function of relative ratio between available water supplies and current water demands.. However, the water rates are not assumed to be equal between the dry and wet regions to reflect the different water situation in each region. Water demands in the dry and wet regions correspond to the total amount of water needed for irrigating alfalfa and other crops in each region. The aridity index is assumed to determine the short-term water supply. Then, the functional form of water rates in each region is specified as:

$$P_W = \pi \left[ \exp \left( \frac{Water\ demand}{Water\ supply} \right) - 1 \right] \\ = \pi \left[ \exp \left( \frac{F[L(W_A^* - Precip \cdot EF_A) + (1 - L)(W_B^* - Precip \cdot EF_B)]}{10^{10} \cdot 0.5^{AI}} \right) - 1 \right]$$

where  $\pi$  is a decelerating parameter.



## CHAPTER 4

### RESULTS

In this chapter, I first develop a baseline scenario to which other scenarios are compared. The three scenarios are then described. Then I explore a range of parameters in each of the three scenarios to address the research questions posed. The model with default parameter values illustrates the baseline projections for alfalfa acreage changes in the dry and wet regions for the next hundred years. To validate the baseline model, I use the current trend in cropland-use change.

#### **Time Frame**

The model uses an annual time scale from year zero to year 100 in the calculations. The land-use change decisions are made on a yearly basis as farmers usually schedule their farming activities based on the information from the previous year (e.g., lagged prices) and one year is naturally suitable for a growing season for most of crops. In this context, short-term decisions like monthly cropping of alfalfa are assumed to aggregate to annual changes.

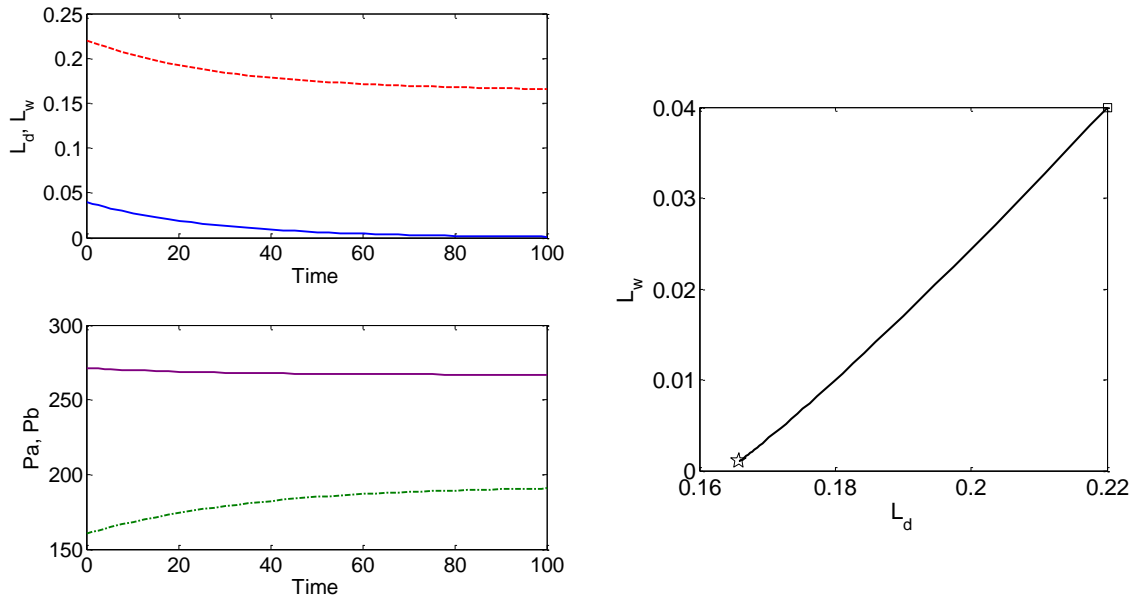
#### **Alfalfa acreage changes**

Crop areas are expressed as fractions of the total land area devoted to each crop within each region. Because the amount of agricultural land is assumed to be the same

across the regions, fractions of cropland devoted to certain crops can be interpreted as land areas devoted to those crops in absolute terms. It is only a matter of scaling.

#### 4.1 Baseline Model

The cropland area devoted to alfalfa has steadily diminished from 1993 to 2013 in the United States. In the last two decades, it has decreased by nearly 6.8 million acres throughout the western and eastern US as a whole. In the east, the amount of land devoted to alfalfa has declined by about 31.5% in the last decade, while it has dropped by about 9.5% in the west for the same time period (see Figure 1.5). These figures show that alfalfa is more quickly fading out of rain-fed areas (i.e., the midwestern and eastern US)



**Figure 4.1.** Time series of fractions of crop areas (left top) and crop prices (left bottom) and phase plane of fractions of crop areas of the baseline case. The dashed red line and solid blue line in the left top figure denote fractions of alfalfa and other crops acreages, respectively. The dashed green line and solid purple line in the left bottom figure represent prices of alfalfa and other crops, respectively. The square marker and star marker in the right figure are the initial and end points of the phase portrait, respectively.

than in dry areas (i.e., the western US). However, due to pressure for land-use change for urbanization and other profitable crops, the overall trend of both regions is the decline of alfalfa acreages. As of 2013, the fractions of acreage planted with alfalfa to the total principle crops acreage are approximately 21.8% and 4% for the western and non-western US, respectively. These numbers were used as default values of the initial alfalfa acreage fractions for the dry and wet regions in the model. That is,  $L_{dry}(0) = 0.22$  and  $L_{wet}(0) = 0.04$ .

The top-left panel of Figure 4.1 shows the time series of percentage changes of alfalfa acreage in the dry and wet regions. Under the baseline assumptions, the model predicts that percentages of alfalfa acreages will decrease constantly in both regions, with the rapid rate of change for the wet region compared to the dry region (see Figure 4.1). Therefore, the results from the baseline scenario are consistent with the overall trend of alfalfa acreage changes.

### **Prices of alfalfa and other crops**

Depending on conditions at a given location, crop prices vary widely across regions. However, I invoke the law of one price for simplicity and clarity in result interpretation. In other words, there is only one price of alfalfa or other crops throughout the dry and wet regions.

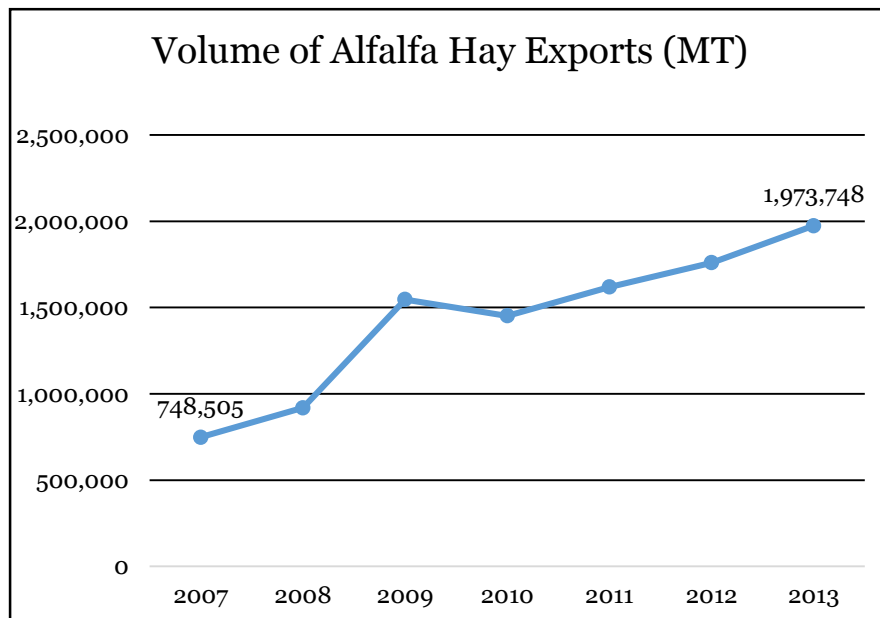
As the supply of alfalfa becomes tighter as a result of the overall decrease in alfalfa acreages, the average annual price of alfalfa hay almost doubled from \$102.5 per ton in 2005 to \$205.8 per ton in 2013. On the demand side, the rise in alfalfa price is partly due to the rapid increase in alfalfa hay exports to foreign countries, including the United Arab Emirates and China, over the past 5 years since 2007. The bottom-left panel

of Figure 4.1 shows that alfalfa hay prices steadily increase as fractions of cropland devoted to alfalfa decline in both regions. Thus, the model prediction of alfalfa price is compatible with the current rising trend of alfalfa prices. For prices of other crops, I refer to the future USDA's projections for corn and soybean prices.

## 4.2 Three Scenarios

**First Scenario:** International demands for alfalfa continue to grow (or at least stay high).

According to Putnam, Mathews, & Sumner (2013), the percentage of alfalfa hay exports has increased from 1.5% in 2007 to 4.3% in 2012, while the percentage of exports of alfalfa hay grown in western states has soared from 5% in 2007 to 12.5% in 2012.



**Figure 4.2.** Alfalfa hay exports from 2007 to 2013. (Source: Foreign Agricultural Service U.S. Trade)

Figure 4.2 shows that the volume of alfalfa hay exported has more than doubled in the 2007-2013 period from 0.7 million metric tons in 2007 to 1.9 million metric tons in 2013. While Japan and Korea have been the regular major importers of US alfalfa hay, this rapid increase is mainly due to the United Arab Emirates and China. The United Arab Emirates imported 27,946 metric tons of alfalfa hay in 2007 and increased more than 23 times to 661,569 metric tons in 2013. China's alfalfa hay imports have increased about 250 times from 2,321 metric tons in 2007 to 576,652 metric tons in 2012.

Although there are many factors that make it difficult to accurately predict the future international market demands for alfalfa hay, it is anticipated that overseas demands for alfalfa will grow due to increasing demand for dairy products and scarce land and water resources in the Middle East and Asia (Fuller, Huang, Ma, & Rozelle, 2006; Putnam et al., 2013). In the simulation, alfalfa hay exports are increased 2 times, 5 times, and 10 times compared to the baseline scenario to see how increasing overseas demand for alfalfa will impact the distribution of crop production across the dry and wet regions.

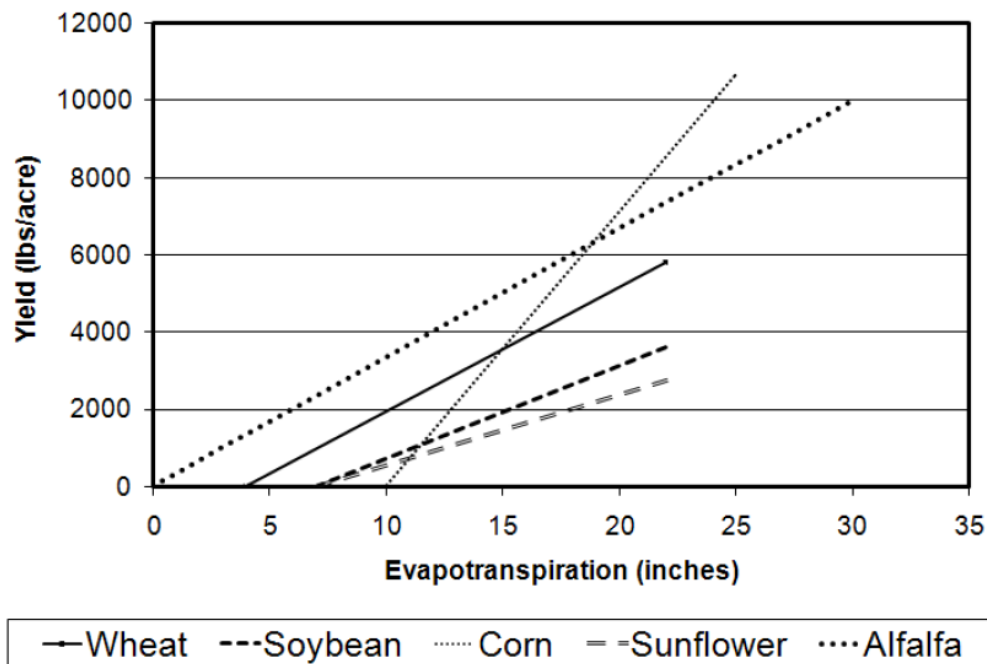
**Second Scenario:** Deficit irrigation is widely imposed in the water-scarce dry region.

Alfalfa is a “good candidate for deficit irrigation” because it is well adapted to dry climates (i.e., drought resistant) as discussed in the introductory chapter and has the ability to go dormant when crop water use or evapotranspiration cannot be fully satisfied (Bauder et al., 2011). Furthermore, because alfalfa is a cool season crop, it “grows slowly and blooms quickly” during the hot and dry summer, which reduces both the quantity and quality of alfalfa harvested (Glennon, 2009). For this reason, turning irrigation of alfalfa fields off during midsummer (usually July and August) seems a reasonable choice

under limited water situations. In short, due to these characteristics, alfalfa can be deficit irrigated to conserve water under severe water stress, freeing up water for other purposes.

Like most other perennial forages, there is a positive linear relationship between yield and water applied for alfalfa (Shewmaker et al., 2013). In other words, as you decrease crop evapotranspiration (i.e., water transpired through crops), the yield will decrease (see Figure 4.3). Figure 4.3 shows that the dormancy trait of alfalfa makes it less susceptible to yield loss from reduced evapotranspiration than corn, soybeans, sunflowers, and winter wheat. Only alfalfa produces some harvests when evapotranspiration is almost close to zero among those crops.

I use the finding from Hanson, Snyder, & Putnam (2007) to simulate the impacts of the second scenario on cropland use. They measured yield and evapotranspiration in deficit irrigated alfalfa fields in July and August. Their result suggests that evapotranspiration is conserved by 224-239 mm at the expense of alfalfa yields 4.68-6.47 tons/ha.



**Figure 4.3.** Yield response to evapotranspiration for alfalfa, corn, soybeans, sunflowers, and winter wheat. (Source: adapted from Bauder, Schneekloth, & Bauder)

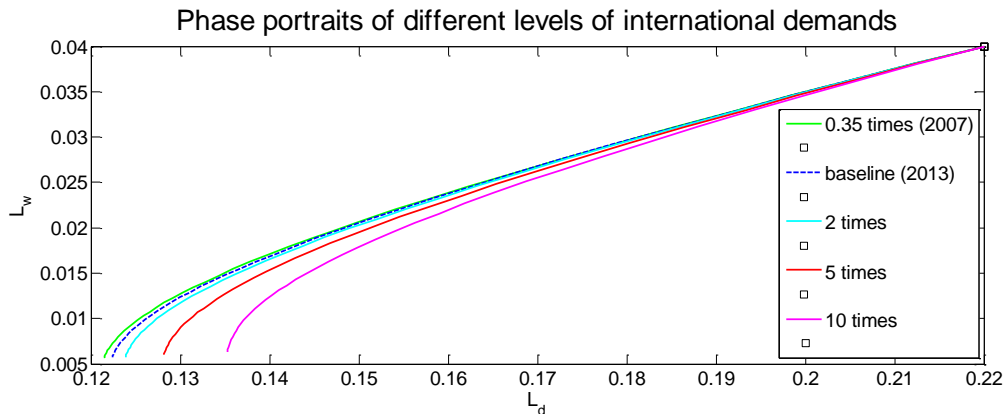
**Third Scenario:** Long-term droughts persist or intensify, leading to reduced precipitation.

According to Maliva & Missimer (2012), drought refers to a “temporary, recurring reduction in the precipitation” at a given place in a broad sense. Because aridity is a long-term climate condition, both the dry and wet regions have drought periods. However, due to the higher variation in precipitation in dry regions, dry regions are more vulnerable to droughts than wet regions, causing severe consequences in the dry regions.

Drought is one of the major reasons for water scarcity in the dry regions. To investigate how farmers cope with the water-limited situation, I reduce the precipitation of the dry region by 2 inch, 5 inch, and 10 inch compared to the baseline scenario.

### 4.3 Simulation Results

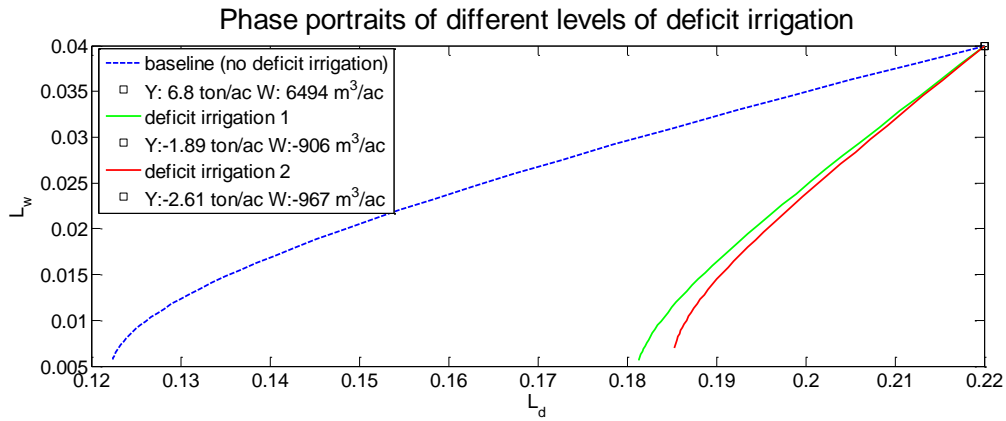
#### First scenario results:



**Figure 4.4.** Phase portraits of different levels of international demands for alfalfa.  $L_d$  and  $L_w$  are the percentages of alfalfa acreage in the dry and wet regions, respectively. The dashed blue line is the baseline case. The light blue line is when alfalfa exports increase two times, the red line five times, and the purple line ten times, respectively.

The increase in alfalfa exports slows down the rate of reduction in the percentage of alfalfa acreage in the dry region. The percentage of land devoted to alfalfa at the end point is 13.5% for the ten times increase in international demand for alfalfa, while it is 12% for the baseline scenario. For the wet region, there is not much difference shown in the cropland percentage change.

### Second scenario results:

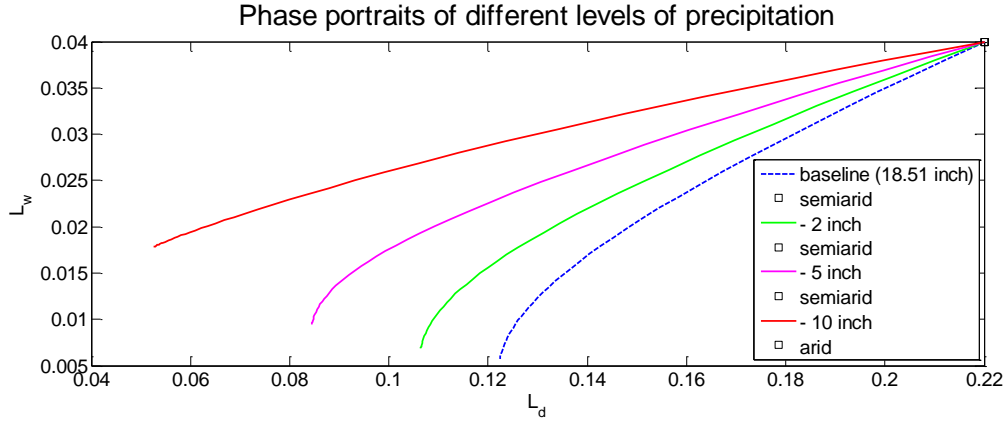


**Figure 4.5.** Phase portraits of different levels of midsummer deficit irrigation in the dry region.  $L_d$  and  $L_w$  are the percentages of alfalfa acreage in the dry and wet regions, respectively. The dashed blue line is the baseline case. The light green line is when 906  $m^3$ /acre of water is conserved with yield loss of 1.89 ton/acre (deficit irrigation 1). The red is when 967  $m^3$ /acre of water is conserved with yield loss of 2.61 ton/acre (deficit irrigation 2).

For deficit irrigation 1, farmers in the dry region lose 1.89 tons of alfalfa per acre compared to the baseline scenario, but can save 906 cubic meter of water per acre. For deficit irrigation 2, farmers in the dry region lose 2.61 tons of alfalfa per acre compared to the baseline scenario, but can save 967 cubic meter per acre. After deficit-irrigating alfalfa fields in the dry region, the result shows that the rate of decrease in alfalfa acreage slows down dramatically. While the percentage of alfalfa acreage decreases by about 10% in the dry region in the baseline case, the counterparts with deficit irrigation 1 and 2 are only 4% and 3.5%, respectively. It suggests that farmers in the dry region use deficit-driven conserved water to expand alfalfa acreage instead of other crops.



### Third scenario results:



**Figure 4.6.** Phase portraits of different levels of precipitation in the dry region.  $L_d$  and  $L_w$  are the percentages of alfalfa acreage in the dry and wet regions, respectively. The dashed blue line is the baseline case. The light green line is when precipitation decreases by two inch in the dry region, the purple line five inch, and the red line ten inch, respectively.

The decrease in precipitation accelerates the rate of decrease in fraction of alfalfa acreage in the dry region. At the end point of the simulation, the percentage of alfalfa acreage in the dry region decreases by 45.5% to 12% of the dry cropland area for the baseline scenario, but it decreases by about 77% to 5% of the dry cropland area in the minus-10-inch precipitation scenario. This result indicates that as water becomes scarcer during the drought, farmers more quickly switch to crops that make more economic use of the limited water.

It turns out that the drastic decrease in alfalfa acreage in the dry region has a positive effect on alfalfa acreage increase in the wet region. Because the dry and wet regions are coupled with each other through the alfalfa hay market, the drought-driven supply shortage of alfalfa hay in the dry region has raised the alfalfa price, which in turn, made alfalfa more profitable in the wet region. As a result, the pace of decrease in alfalfa acreage has slowed down in the wet region.

## CHAPTER 5

### CONCLUSIONS AND DISCUSSION

Land and water are the limited resources that are fundamentally essential to meet our demands for food, housing, and other basic necessities. In this study, I investigated the different pathways of cropland development under different water situations. By simplifying the United States into a binary world of the arid West and the humid East, the impact of water scarcity on crop production was clearly exposed. The results of this study suggest that 1) in order to cope with the water limited situation, farmers will shift to less water-intensive crops that hold higher economic values and 2) in drought years, farmers can deficit-irrigate their alfalfa fields, leaving more water to be used for other purposes. The first finding implies that when water is scarce, the limited land will be used for the purpose of creating higher values with less water. This further implies that, if the scope of the study is not restricted only to agriculture, removing agricultural fields from production and converting the land and conserved water to urban and industrial sectors would be the most likely future. The second finding implies that without the removal of agricultural land from production, there could be multiple ways of meeting (or alleviating) water demands from various sectors. Apart from deficit irrigation, farmers might be able to continue farming by increasing irrigation efficiency, e.g., switching from gravity irrigation to micro-irrigation. Also, the model results generally suggest that alfalfa production gradually shifted out of wet regions into arid regions under the three scenarios. This implies that the limited western irrigation water

used to grow alfalfa is the price for the consumption of dairy products such as milk, cheese, butter, ice cream, and yogurt.

Results from the cropland-use change model in this study are fundamentally driven by relative advantages that alternative crops have over alfalfa in terms of cash value and crop water use. For this reason, every scenario in this study shows a general trend of decline in alfalfa acreage (or rise in alternative crop acreage) in both the dry and wet region. It explains why the model generally predicts long-term outcomes where the fraction of alfalfa acreage in the wet region goes to zero and the equivalent of the dry region goes to some point below the original point over the study period. The fraction of land devoted to alfalfa in the dry region does not go up until the system has an extreme demand for alfalfa. This finding suggests that a combination of rise in dairy demand and growing water shortages around the world could eventually lead to the expansion of alfalfa acreage in a region like the western US.

There is great uncertainty regarding how global climate change will affect regional weather conditions. That said, it is highly probable that arid and semiarid regions will experience more frequent and prolonged droughts in the future. As demonstrated in the third scenario, the fraction of land devoted to alfalfa (or the total alfalfa acreage) in a region can be used, in conjunction with other trends, as a signal of aggravated water scarcity or competition for water in the region. Moreover, the model shows that with extended droughts, the alfalfa acreage decrease in the wet region is suppressed to some extent. Theoretically, this provides an opportunity for virtual water transfer from wet regions to dry regions, which makes sense in terms of water use efficiency.

As the US is often seen as a microcosm of a variety of climate regions in the world, the model developed in this study may be generalized to represent the dry and wet

parts of the world and their land-use change. Regardless of whether water is scarce or not, in order to sustain the population and regional economies, every climate region is required to produce food, which relies on freshwater resources. That is, either self-growing or exporting regions have to pay the price for land and water to provide food. Water-stressed arid regions (e.g., the Middle East and some parts of Asia) strategically seek to supplement local water deficit through the import of forage crops like alfalfa from other regions. In recompense for export proceeds, these exporting regions (e.g., the arid western US) should bear the cost of water for crop production. Therefore, the increase in alfalfa exports shown in the first scenario reflects not only newly available economic opportunities for local farmers in exporting regions, but also the changing land and water situations among arid and wet regions in the world. As a globalized commodity, alfalfa—as well as other water-intensive, low-value crops—may potentially be used, in conjunction with other factors, to study patterns of how much we pay for food security in regards with the limited water and how this payment changes around the world over time.

This stylized model involves a number of simplifying assumptions with an aim for clarity in result interpretation. However, as typical in such a model, its caveats and limitations must be properly recognized. For example, crop prices and fractions of land devoted to crops are based on 2013 levels, which have been influenced by a special period that includes the 2007-2008 world food and global finance crises. In that period, major world crop prices soared, including alfalfa, and housing prices plummeted in the aftermath of the financial crisis. In the following recession, the pressure for land use was lessened and crop price rises provided economic opportunities for farmers (usually large-scale farmers who have access to farm loan); the combination of these two events decelerated land-use change from agriculture to urban uses. Such unusual historical

events can have lasting impacts on land use. Therefore, explicitly incorporating these types of events into the model can significantly alter the results.

Another important caveat is that the model assumes homogeneity in alfalfa production processes within each region. This masks significant regional heterogeneity in reality. Discrepancies in climate, soil types, water availability, regional markets, and transportation costs within the dry and wet regions can create bias in estimating the production of crops. In addition, by assuming fully-irrigated agricultural fields and a uniform and flat water price structure, the model does not capture the fact that farmers face wildly different degrees of surface water shortage and varying groundwater pumping costs due to declining water levels. Furthermore, the model does not include temporal fluctuations in crop prices and precipitation levels, which could also significantly change the model results.

The water scarcity problem in arid regions will not be easy to address since it entails a complex set of issues such as food security, increasing demand from urban and industrial use, and uncertain climate changes. Among those issues, only some specific aspects of the problem are addressed in this study. Taking this as a stepping stone, I have identified several potential areas of the model extension. For example, formulating the structure of relative advantages for selected crops differently will further our understanding of multiple regimes in a coupled ecological-economic system of land use. In addition, by addressing variability of prices and climate conditions, bimodal surface water and groundwater cost structure, and heterogeneous characteristics of the climate zones in the model, I will be able to improve the model results and gain more insights on crop production in a water-stressed region.

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## APPENDIX A

### LIST OF SYMBOLS AND DEFAULT PARAMETER VALUES

Symbol	Description	Unit	Default value(s):
Subscript A	Alfalfa	n/a	
Subscript B	Other crops	n/a	
Subscript C	Dairy products	n/a	
Superscript D	Dry region	n/a	
Superscript W	Wet region	n/a	
$Y$	Average annual actual crop yield when soil salinity is considered	tons/acre	
$Y_m$	Expected crop yield when $EC_e < EC_{e,threshold}$	tons/acre	
$\beta$	Maximum expected crop yield when the optimal amount of water is applied to the field	tons/acre	$\beta_A^D=6.8, \beta_B^D=4.953,$ $\beta_A^W=3.3, \beta_B^W=4.191$
$EC_e$	Mean electrical conductivity of the saturation extract for the root zone	dS/m	$EC_e^D=4.5, EC_e^W=0.5$
$EC_{e,threshold}$	Electrical conductivity of the saturation extract at the threshold of $EC_e$ when crop yield first reduces below $Y_m$	dS/m	$EC_{e,threshold,A}=2,$ $EC_{e,threshold,B}=1.7$
$d$	Reduction parameter in yield per increase in $EC_e$	%/(dS/m)	$d_A=7.3, d_B=12$
$C$	Costs of growing and harvesting crops	dollars/acre	
$F$	Total amount of arable land planted to crops	Acres	$F^D=151.877*10^6,$ $F^W=151.877*10^6$
$W^*$	Crop water requirement per acre	$m^3/acre$	
$VWC$	Virtual water content of crops	$m^3/ton$	$VWC_A^D=955,$ $VWC_B^D=775,$ $VWC_A^W=295,$ $VWC_B^W=283$
$Precip$	Precipitation	$m^3/acre$	$Precip^D=1903,$ $Precip^W=3667$
$Irri$	Irrigation water	$m^3/acre$	
$ET_0$	Reference crop evapotranspiration	$m^3/acre$	
$ET_p$	Potential evapotranspiration	$m^3/acre$	
$v > 0$	Soil water storage (or retention) parameter for a specific crop		$v_A=3, v_B=1.5$
$P_U$	Average hourly wage rate	dollars/hour	$P_V^D=10, P_V^W=13$
$U$	Average labor hours per acre for crops	hours/acre	$V_A=2.85, V_B=2.3$
$E$	Crop-specific extra lump sum cost	dollars/acre	$E_A=720, E_B=775.33$
$P$	Price of crops	dollars/ton	

$P_C$	Price of dairy products	dollars/lb	0.22
$\mu$	Price coefficient for a specific crop	dollars/ton	$\mu_A=206, \mu_B=151.6$
$b_1 > 0$	Demand elasticity of the crop price		.5
$b_2 < 0$	Supply elasticity of the crop price		-.5
$S$	Total quantity supplied of goods	tons	
$D$	Total quantity demanded of goods	tons	
$D^{(R)}$	Regional quantity demanded	tons	
$D^{(I)}$	International quantity demanded	tons	$D_A^{(I)}=2*10^6,$ $D_B^{(I)}=23.865049*10^6$
$x_C$	Consumption of C in a region	tons	
$x_B$	Consumption of B in a region	tons	
$0 < \alpha < 1$	Income partitioning parameter		.3
$M$	Total income of a region	dollars	$1.231*10^{12}$
$c$	Conversion rate of milk production to eaten alfalfa	%	$0.16*0.000453592$
$P_W$	Price of water	$dollars/m^3$	
$AI$	Aridity index		$AI^D=5, AI^W=0.75$
$r$	Time-adjusting parameter		0.00005
$\pi$	Decelerating parameter		0.22

APPENDIX B  
MATLAB CODE

*A script file—make\_landuse\_March.m*

% make\_landuse\_March.m

% Master's thesis coding

% The land use change differential equation

% Booyoung Kim

clear, close all

global Ya\_dry Yb\_dry Ya\_wet Yb\_wet guess ua ub c alp M Pc QIa QIb b1 b2

global Wstara\_dry Wstara\_wet Wstarb\_dry Wstarb\_wet AI\_dry AI\_wet ka kb

global R\_dry R\_wet Pw\_dry Pw\_wet Ca\_dry Cb\_dry Ca\_wet Cb\_wet

global Pa Pb F\_dry F\_wet

%Prices%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

F\_dry= 151.877\*10<sup>6</sup>; % (Acres)

F\_wet= 151.877\*10<sup>6</sup>;

ua=206; % Price coefficient for alfalfa

ub=151.6; % Price coefficient for other crops

Pc=0.22; % Whole milk prices (proxy for dairy products) (dollars/lb)

alp=.3; % a fraction of income spent on good C

c=0.16\*0.000453592; % a conversion rate of demand from dairy products to alfalfa

M=1.231\*10<sup>12</sup>; % Food expenditures by families and individuals (\$1,231 billion in 2013)

QIa=2\*10<sup>6</sup>; % metric ton

$QIb=23.865049 \times 10^6$ ; % metric ton

$b1=0.5$ ; % price elasticity coefficient of the crop demand

$b2=-0.5$ ; % price elasticity coefficient of the crop supply

$AI\_dry=5$  % Aridity Index for the dry region

$AI\_wet=0.75$  % Aridity Index for the wet region

$R\_dry=1903-0$ ; % (=18.51 inch) Average annual precipitation in the dry region (CA) ( $m^3/acre$ )

$R\_wet=3667$ ; % (=35.67 inch) Average annual precipitation in the wet region (IA) ( $m^3/acre$ )

%Yield%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

$\beta_{dry}=6.8$ ; % Average annual yield for alfalfa in the dry region (CA) (tons/acre)

$\beta_{b\_dry}=4.953$ ; % Average annual yield for other crops in the dry region (tons/acre)

$\beta_{wet}=3.3$ ; % Average annual yield for alfalfa in the wet region (IA) (tons/acre)

$\beta_{b\_wet}=4.191$ ; % Average annual yield for other crops in the wet region (tons/acre)

$E_{Ce\_dry}=4.5$ ; % mean electrical conductivity of the saturation extract for the

% root zone in dry climate

$E_{Ce\_wet}=0.5$ ; % mean electrical conductivity of the saturation extract for the

% root zone in wet climate

$EC_{tha}=2$ ; % electrical conductivity of the saturation extract at the threshold

% of  $E_{Ce}$  when crop yield first reduces below the maximum expected crop

% yield (alfalfa)

$EC_{thb}=1.7$ ; % electrical conductivity of the saturation extract at the

% threshold of ECe when crop yield first reduces below the maximum expected

% crop yield (corn)

da=7.3; % percentage reduction in yield per increase in ECe (alfalfa)

db=12; % percentage reduction in yield per increase in ECe (corn)

Ya\_dry=beta\_dry\*(1-da/100\*max(0,ECe\_dry-ECtha))

Yb\_dry=betb\_dry\*(1-db/100\*max(0,ECe\_dry-ECthb))

Ya\_wet=beta\_wet\*(1-da/100\*max(0,ECe\_wet-ECtha))

Yb\_wet=betb\_wet\*(1-db/100\*max(0,ECe\_wet-ECthb))

%Cost%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Wstara\_dry=955; % Virtual water content of alfalfa in the dry region (CA) (m<sup>3</sup>/ton)

Wstarb\_dry=775 % Virtual water content of other crops in the dry region (m<sup>3</sup>/ton)

Wstara\_wet=295; % Virtual water content of alfalfa in the wet region (IA) (m<sup>3</sup>/ton)

Wstarb\_wet=285; % Virtual water content of other crops in the wet region (m<sup>3</sup>/ton)

ka=3; % Alfalfa coefficient for soil water storage

kb=1.5; % Other crop coefficient for soil water storage

%Guess the price of other crops%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

dummyPb = linspace(10,10000,10001);

figure(1000)

initialLd = .22;

```

initialLw = .04;

plot(dummyPb,ub*[((1-alp)*M./dummyPb+QIb).^b1*(F_dry*(1-initialLd)*Yb_dry+F_wet*(1-
initialLw)*Yb_wet).^b2]-dummyPb)

hold on

plot([0 10000],[0 0], '--k')

ylim([-1 1])

guess = input('Booyoung, guess Pb!: ')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[T,V]=ode45(@landuse,[0 100],[initialLd initialLw]);

%Plot%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(1), plot(V(:,1),V(:,2),'k','linewidth',2); hold on

plot(V(1,1),V(1,2),'sqk')

plot(V(end,1),V(end,2),'pk','markersize',12)

% xlim([0 1]), ylim([0 1])

set(gca,'fontsize',16)

% axis equal

xlabel('L_d'), ylabel('L_w')

set(gcf,'position',[100 200 550 450])

figure(2), subplot(2,1,1)

plot(T,V(:,1),'--r','linewidth',2), hold on

plot(T,V(:,2),'b','linewidth',2)

```



```

set(gca,'fontsize',16)
xlabel('Time'), ylabel('L_d, L_w')
set(gcf,'position',[750 50 600 700])

subplot(2,1,2)
Ld = V(:,1);
Lw = V(:,2);
Pat=ua*[(c*alp*M/Pc+QIa)^b1].*(F_dry*Ld*Ya_dry+F_wet*Lw*Ya_wet).^b2;
for t = 1:length(T)
    Pb=fzero(@(Pbx) ub*(((1-alp)*M./Pbx+QIb).^b1)*(F_dry*(1-Ld(t))*Yb_dry+F_wet*(1-
Lw(t))*Yb_wet).^b2-Pbx,guess);
    Pbt(t) = Pb;
    guess = Pb;
end
plot(T,Pat,'-','color',[0 0.5 0],'linewidth',2), hold on % green
plot(T,Pbt,'color',[0.5 0 0.5],'linewidth',2), hold on % purple
set(gca,'fontsize',16)
xlabel('Time'), ylabel('Pa, Pb')

```

*A function file—landuse.m*

```
% landuse.m
```

```
function dVdt = landuse(t,V)
```

```

global Ya_dry Yb_dry Ya_wet Yb_wet guess ua ub c alp M Pc QIa QIb b1 b2
global Wstara_dry Wstara_wet Wstarb_dry Wstarb_wet AI_dry AI_wet ka kb
global R_dry R_wet Pw_dry Pw_wet Ca_dry Cb_dry Ca_wet Cb_wet
global Pa Pb F_dry F_wet

Ld = V(1);
Lw = V(2);

%Price%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Pa=ua*[(c*alp*M/Pc+QIa)^b1]*(F_dry*Ld*Ya_dry+F_wet*Lw*Ya_wet)^b2
Pb=fzero(@(Pbx) ub*(((1-alp)*M./Pbx+QIb).^b1)*(F_dry*(1-Ld)*Yb_dry+F_wet*(1-
Lw)*Yb_wet).^b2-Pbx,guess)

guess = Pb;

Wd_dry=F_dry*Ld*(Ya_dry*Wstara_dry*(1+AI_dry^(-ka))^(1/ka)-R_dry)+F_dry*(1-
Ld)*(Yb_dry*Wstarb_dry*(1+AI_dry^(-kb))^(1/kb)-R_dry)
Wd_wet=F_wet*Lw*(Ya_wet*Wstara_wet*(1+AI_wet^(-ka))^(1/ka)-R_wet)+F_wet*(1-
Lw)*(Yb_wet*Wstarb_wet*(1+AI_wet^(-kb))^(1/kb)-R_wet)

Pw_dry=0.22*(1.001^(Wd_dry/((0.5^AI_dry)*10^10))-1); % the price of water in the dry
region (dollars/m^3)
Pw_wet=0.22*(1.001^(Wd_wet/((0.5^AI_wet)*10^10))-1); % the price of water in the wet
region (dollars/m^3)

Ea=720; % Extra lump sum cost for alfalfa

```

Eb=775.33; % Extra lump sum cost for other crops

Pv\_dry=10; % hourly wage rate in the dry region

Pv\_wet=13; % hourly wage rate in the wet region

Va=2.85; % labor hours per acre for alfalfa

Vb=2.3; % labor hours per acre for other crops

Ca\_dry=Pw\_dry\*max(o,((Ya\_dry\*Wstara\_dry-o)-R\_dry\*(1+AI\_dry^(-ka))^(-1/ka)))+Pv\_dry\*Va+Ea;

Cb\_dry=Pw\_dry\*max(o,(Yb\_dry\*Wstarb\_dry-R\_dry\*(1+AI\_dry^(-kb))^(-1/kb)))+Pv\_dry\*Vb+Eb;

Ca\_wet=Pw\_wet\*max(o,(Ya\_wet\*Wstara\_wet-R\_wet\*(1+AI\_wet^(-ka))^(-1/ka)))+Pv\_wet\*Va+Ea;

Cb\_wet=Pw\_wet\*max(o,(Yb\_wet\*Wstarb\_wet-R\_wet\*(1+AI\_wet^(-kb))^(-1/kb)))+Pv\_wet\*Vb+Eb;

dVdt = zeros(2,1);

dVdt(1) = 0.00005 \* Ld\*(1-Ld)\*[(Pa\*Ya\_dry-Ca\_dry)-(Pb\*Yb\_dry-Cb\_dry)];

dVdt(2) = 0.00005 \* Lw\*(1-Lw)\*((Pa\*Ya\_wet-Ca\_wet)-(Pb\*Yb\_wet-Cb\_wet))

end